

A mapping of global warming research based on IPCC AR4

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Received: 13 June 2008 / Accepted: 13 August 2008 / Published online: 25 September 2008
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Abstract It is easy to get lost in the vast amount of knowledge that is currently produced. In this study, to get a comprehensive picture of current scientific knowledge about global warming issues, we developed a mapping framework for global warming research based on the relationships between nature and human society. The mapping includes seven phases: (1) socioeconomic activity and greenhouse gas emissions, (2) carbon cycle and carbon concentration, (3) climate change and global warming, (4) impacts on ecosystems and human society, (5) adaptation, (6) mitigation, and (7) social systems. We applied the findings of the *Intergovernmental Panel on Climate Change Fourth Assessment Report* to the mapping. The quantity of research results and their reliability were analyzed on the basis of expert judgment to better understand the extent to which current scientific knowledge provides answers to society's major concerns. The quantity and reliability of answers have increased in phases 2 and 3 relative to research in the *Third Assessment Report*. Although a large quantity of results have been produced in phases 4 and 6, they are not always sufficient. More studies are required in phases 1, 5, and 7, and the reliability of

existing knowledge needs to be improved in these phases. Mapping global warming issues enabled us to visually comprehend the numerous and varied parts of global warming research as a whole and to discern gaps in knowledge and other research shortfalls.

Keywords Adaptation · Climate change · Mitigation · Research mapping · Structuring knowledge

Introduction

Research activities on climate change and global warming have experienced a remarkable worldwide increase in recent years. Since the release of *The Stern Review* (Stern 2007) and the *Intergovernmental Panel on Climate Change Fourth Assessment Report* (IPCC AR4) (IPCC 2007a, b, c) in 2007, climate change issues have been prioritized in both national and international arenas. Given that post-Kyoto arguments remain active, and the Bali Roadmap was defined at the Conference of the Parties, 13th Session (COP13), there is an urgent need to develop an international initiative to increase efforts to reduce greenhouse gas (GHG) emissions at the local and global levels. However, conventional research has addressed these problems from the specific viewpoints of particular fields and, up to this point, it has been very difficult to present a comprehensive view of the future. Designing sustainable countermeasures for addressing global warming requires an approach that unifies the various aspects of climate change, including impact assessment, prediction, mitigation and adaptation measures, policy issues, and social issues. It is essential to attack the problems from a wide range of viewpoints from different academic fields, including natural science, engineering, agriculture, economics, and political science.

Electronic supplementary material The online version of this article (doi:10.1007/s11625-008-0058-9) contains supplementary material, which is available to authorized users.

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Recognizing the need for a new academic discipline of sustainability science, which must adopt a comprehensive and holistic approach to identification of problems and perspectives involving the sustainability of global, social, and human systems, the University of Tokyo inaugurated the Integrated Research System for Sustainability Science (IR3S) and invited universities and research institutes to set up a nationwide research network in Japan (Komiya and Takeuchi 2006). IR3S has conducted flagship projects with five participating universities (the University of Tokyo, Kyoto University, Osaka University, Hokkaido University, and Ibaraki University) and six cooperating organizations (Toyo University, the National Institute for Environmental Studies, Tohoku University, Chiba University, Waseda University, and Ritsumeikan University). Through the cooperation and participation of these universities and organizations, the flagship projects represent models of the type of transdisciplinary research needed to achieve sustainable society. This study is part of the flagship project, “sustainable countermeasures to mitigate and adapt to global warming” (hereafter, FP-GW). The IR3S participating universities and cooperating organizations already have knowledge and experience, and have contributed to research on global warming. Active communication, linkage of knowledge and experience, and mediation between experts in different fields and decision-makers is effective in mobilizing knowledge into action, and these boundary management functions can be performed effectively through various organizational arrangements and procedures (Cash et al. 2003). The integration of our activities will lead to a new vision for sustainable society, and takes the following items into consideration:

- Clarification of certainties, uncertainties, inadequacies, and challenges in addressing global warming by organizing current scientific knowledge and restructuring the statement and/or solution of the problem.
- Utilization of the best research capacities of the participating universities and coordinating to conduct research that focuses on the mutual relationships among the various fields. Encourage feedback on the results of each study and exchange of information and opinions by researchers.
- Propose multiple designs for society in the twenty-first century, accounting for uncertainties in predictions of global warming, possibility of maladaptation of socio-economic systems, and uncertainties in technical development and available resources.

Global warming research is wide-ranging. Such research is a core part of sustainability science, which is considered to be use-inspired basic research, motivated both by the quest for fundamental understanding and by problem-

solving considerations (Clark 2007; Stokes 1997). As is often the case, just listing and strewing keywords or showing causal connections or relationships among elements is cumbersome and can result in problems that are difficult to understand comprehensively. Mapping approaches are sometimes used to systematically understand complex problems involving many diverse elements. To present a conceptual framework to guide the understanding of the overall issues, examine their constituent elements, and organize existing knowledge on sustainable development, Choucri et al. (2007) proposed a three-dimensional (3D) pillar map with an integrated frame system comprising slice (domain of core concept), ring (dimension of problem and solution), and cell (granular manifestation). Another interesting approach is to draw a research overview map of sustainability science by analyzing the citation network of papers published in academic journals and detecting research domains (Kajikawa et al. 2007). Bozeman (2003) sought to develop conceptual tools and measures that would enable a better understanding of the impacts of scientific research on desired social outcomes with his *Public Value Mapping of Science Outcomes*. Global warming issues can be well structured and visualized by mapping, so that we can comprehensively recognize problems and create and implement compatibly designed and appropriate countermeasures.

In this study, we propose a map of global warming issues to restructure our knowledge. We introduced a framework of seven phases of the global warming process into the mapping. The classification of phases is based on the interaction among human society and nature. This is arbitrarily defined by experts and should be evaluated further in the future. The objective of this study is to reorganize current research results and clarify problems and solutions. We also aim to clarify certainties and uncertainties of scientific knowledge and to identify higher and lower priority areas for future research.

Overview of the research

This study followed the methodology below with the cooperation of scientists of climate change including coordinating lead authors (CLAs) or lead authors (LAs) of IPCC.

Development of the mapping framework

Global warming issues were classified into seven phases from the points of view of the process of global warming and the response of human society to it. Keywords and key questions were distributed into each phase from the academic view to analyze current scientific knowledge.

Application of IPCC AR4 findings to the mapping

As a source of comprehensive information of current research results, IPCC AR4 was applied to the mapping framework. The scientific results are summarized and classified into the phases based on bullets of summary for policy makers (SPM) of working groups I–III so as to compare the numbers of the results (quantitative analysis).

Next, the certainty of scientific knowledge in IPCC AR4 was analyzed (qualitative analysis). The findings of IPCC AR4 were reorganized and classified into three ranks of certainty to examine the extent to which scientific knowledge provided answers to the major concerns. The classification was conducted by experts, and is based on the level of reliability indicated in the IPCC report. The ranked IPCC findings were also classified into seven phases for further analysis.

Discussion: answers to key questions of the map

We compared the current scientific results in each phase quantitatively and qualitatively so that we could understand the whole picture of current global warming research. We discussed gaps in scientific knowledge, as well as the research progress and research shortfalls that could affect the decision-making of future directions for research.

Development of the mapping framework: structuring knowledge of global warming issues

Phase classification for mapping

Global warming is caused by the disruption of the balance between nature and human society. To make it easier to understand the complex and wide-ranging elements related to global warming, we need an organizational framework. Therefore, we classified global warming issues into seven phases from the points of view of interactions between global natural systems, socio-economic systems and human systems (Komiyama and Takeuchi 2006). This sequence of phases naturally follows the process and is easy to understand. Similar framing of these processes is used implicitly in the IPCC assessment reports, and is more clearly shown in the reports of the Council for Science and Technology Promotion (Ichikawa 2004; Koike 2006).

1. GHGs and aerosols are emitted and natural environments are changed by the economic activities of human society (“socioeconomic activity and GHG emissions” in Fig. 1).
2. In the natural system, carbon circulates in the atmosphere, in the ocean, and on land through photosynthesis, respiration, decomposition, and other processes. Emitted

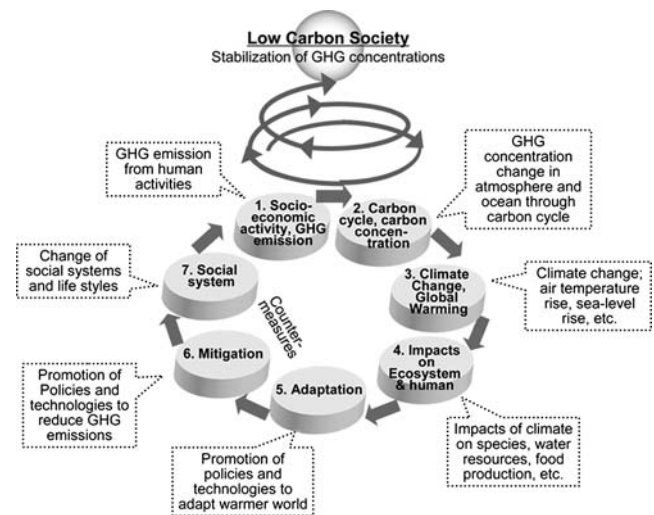


Fig. 1 Framework for understanding global warming

GHGs enter these circulation processes and finally determine the GHG concentration in the atmosphere (“carbon cycle and carbon concentration”).

3. GHGs in the atmosphere cause climate change, such as increases in air temperature and sea level (“climate change and global warming”).
4. Climate change induces various effects on ecosystems and human society, such as submerging of low-lying areas, extinction of species, and changing food production and water resources (“impacts on ecosystems and human society”).
5. To address the impacts of climate change, human society must promote policies and technologies to adapt to a warmer world (“adaptation”).
6. In addition to adapting to a warmer world, human society must also reduce GHG emissions to decrease GHG concentrations in the atmosphere, and must therefore introduce various mitigating policies and technologies (“mitigation”).
7. New social systems should be developed. Changes in social values, lifestyles, and education, and voluntary actions taken by society must occur (“social systems”).

The change of social structure in phase 7 has the possibility of producing new problems, meaning that we will have to look again at the problem with the whole cycle. Interactions between human society and nature will continue, and the issues raised by the process of global warming will be endlessly repeated. This cycle is not at equilibrium but is continually changing based on the dynamic interaction between nature and human society. Therefore, we have to consider problems with the whole cycle continuously. The sequence of the phases will repeat in spirals towards a low carbon society. Based on this

dynamic structure, we created the seven-phase framework of global warming issues shown in Fig. 1. This mapping framework is conceptually clear and easy to understand, yet it is also comprehensive and encompasses a broad range of global warming elements.

Mapping framework and identification of key questions

We created a map of global warming with the seven phases, as shown in Fig. 2. To better represent the issues, we divided each phase into several categories and input major keywords of current research programs in the world into those categories. Generally, items located closer to the center represent more fundamental issues and items located further from the center are more applied. The items closest to the center of the map represent the most fundamental issues in phases 1, 2 and 7; the more serious phenomena and effects in phases 3 and 4; and the highest priority options in phases 5 and 6. The items listed further from the center are the more practical challenges on which society needs to work, especially in phases 1 and 7.

Phase 1 incorporates the industrial structure and basic social structure that determine GHG emissions and relate to the emission inventory, including population and society’s energy demands. In phase 2, the carbon cycle was divided into the atmosphere, hydrosphere, geosphere, and biosphere. The behaviors of GHGs and aerosols, mechanisms of the carbon cycle (e.g., carbon sink), and other environmental elements affecting the carbon cycle are included.

Phase 3 was divided into observation and prediction of climate change, as well as the related uncertainties. Observed global warming items and models predicting the future climate are included here. Phase 4 contains the categories of impacts and risk assessment. Impacts include the direct effects of global warming as well as the indirect or multiple effects associated with other causes. Categories for technology and policy are included in phases 5 and 6. Examples of adaptation technologies are revetments against high storm surges or flooding, and improvement or introduction of genetically modified organisms (GMO) to ensure crop yields in a warmer climate. Adaptation policies include insurance schemes and other types of risk management. Examples of mitigation technologies include energy saving, renewable energy, and carbon capture and storage technologies as well as forest management techniques used to increase the carbon sink. Mitigation policies include creation of an international/national regime to reduce GHG emissions and economic measures, such as emissions trading and clean development mechanism (CDM). The energy sector has strong ties to climate change and plays a very important role in mitigation. However, this sector sometimes has other objectives (e.g., energy security) and there is an enormous amount of research in this area. Therefore, we treated the energy sector separately and minimized the types of energy represented, mainly including those that deal with climate change, energy saving, renewable energy, and other related issues. There are some policies and technologies that relate to both

Fig. 2 Map of the seven phases with keywords from global warming research

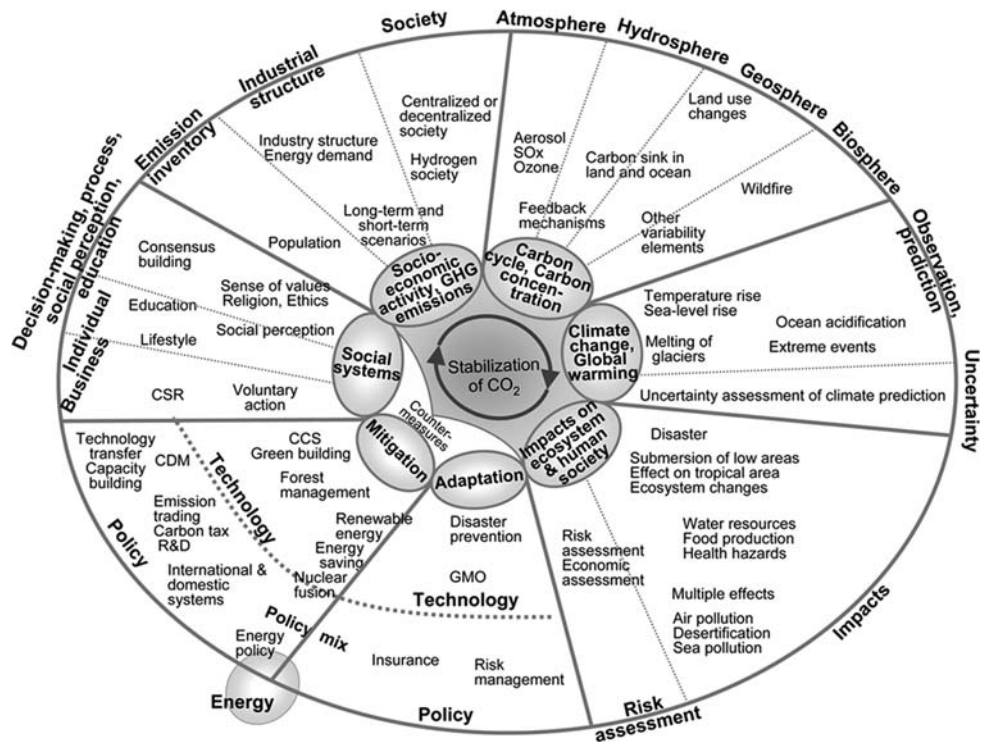


Table 1 Key questions for each phase

Phase	Key questions
1. Socioeconomic activity and GHG emissions	How will the amount of anthropogenic GHG emissions and their emission sources change?
2. Carbon cycle and carbon concentration	How do GHG concentrations change? What is the mechanism of the carbon cycle and what are the environmental variation factors relating to climate change?
3. Climate change and global warming	Does global warming occur? How will the climate change in the future?
4. Impacts on ecosystems and human society	What are the impacts of climate change? What level of climate change will put humans and ecosystems at risk?
5. Adaptation	What kinds of adaptation policies and technologies are required? By how much will adaptation measures reduce the risk?
6. Mitigation	What kinds of mitigation policies and technologies are required for reductions in GHG emissions? How much GHG emission reduction will be possible?
7. Social systems	How can human society change social systems to create a low carbon society? Do the changes contribute to a sustainable society?

GHG greenhouse gas

phases 5 and 6 (e.g., the policy mix or technology portfolio). Phase 7 includes philosophical aspects and the governance of society (e.g., the behavior of businesses and individuals, education, social norms and values, religion, and the decision-making process).

By using this mapping framework and considering the issues in each phase holistically, well-balanced countermeasures against global warming can be developed. The map can be changed in response to feedback from scientists and policy makers or new research results.

To understand the structure and core problem in each phase, we identified key questions that are both representative of each phase and highest on the list of concerns regarding climate change for that phase (Table 1). Of course, there are many underlying issues and more detailed questions in each phase. We used these key questions and our mapping classifications to measure the quantity and reliability of answers that research has thus far provided to society.

Application of IPCC AR4 findings to the mapping

The IPCC is an intergovernmental scientific body established to provide decision-makers and others interested in climate change with an objective source of information about climate change (IPCC 2008). While the knowledge on global warming is vast, IPCC reports are a good source of comprehensive information to help understand current research results regarding global warming. The IPCC provides these reports at regular intervals and released AR4 in 2007, 6 years after the Third Assessment Report (TAR) in 2001 (IPCC 2001a, b, c). The IPCC has three working groups. Working group I (WGI) assesses the physical

scientific aspects of the climate system and climate change. Its latest report is *Climate change 2007: the physical science basis* (IPCC 2007a). Working group II (WGII) assesses the vulnerability of socioeconomic and natural systems to climate change, the negative and positive consequences of climate change, and options for adapting to it. Its latest report is *Climate change 2007: impacts, adaptation and vulnerability* (IPCC 2007b). Working group III (WGIII) assesses options for mitigating climate change through limiting or preventing GHG emissions and enhancing activities that remove them from the atmosphere. Its latest report is *Climate change 2007: mitigation of climate change* (IPCC 2007c). IPCC AR4 consists of these three reports, and our study used the results presented in the SPM of each report for analysis.

Quantitative analysis: research results of IPCC AR4

We tried organizing and restructuring the knowledge on global warming. We assumed that the results summarized by the bullets in the three SPMs represent the essence of the current state of scientific knowledge and applied them to the mapping. We summarized and classified the results into each phase (Fig. 3). This visual map makes it easier to grasp the distribution of research in each phase and the types of results that have been obtained. The number of scientific results obtained by each WG in each phase are shown in Fig. 4. It is clear that WGI deals primarily with phases 2 and 3, WGII with phases 4 and 5, and WGIII deals with phases 1, 6, and 7.

There are a larger number of results in phases 4 (number 75) and 6 (number 82). Many of the results obtained in phase 4 deal with the observed impacts of global warming and predictions of future impacts in regions and sectors,

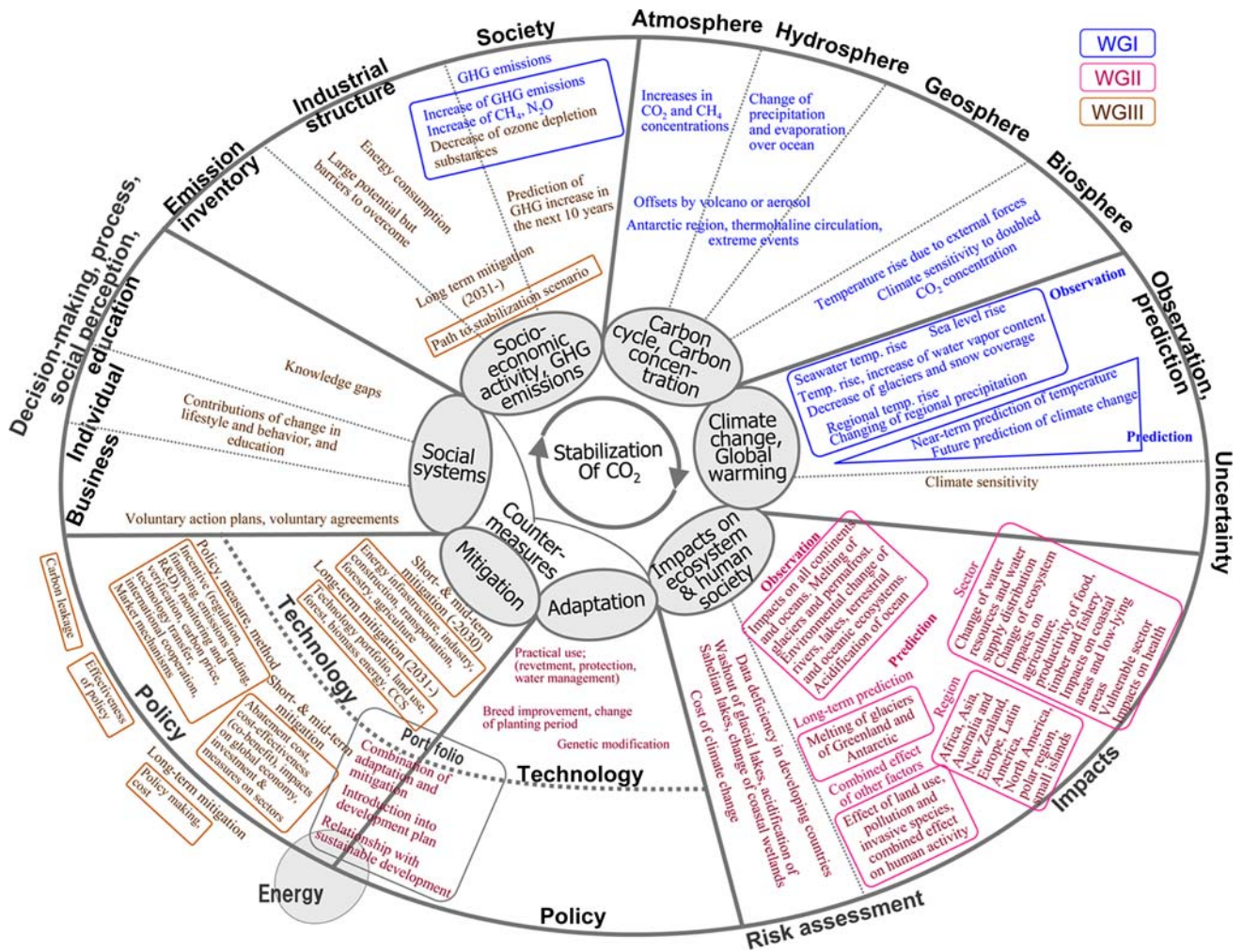


Fig. 3 The mapping of scientific results listed in the *Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4)*. Blue Results from working group I (WGI), pink WGII, and brown WGIII

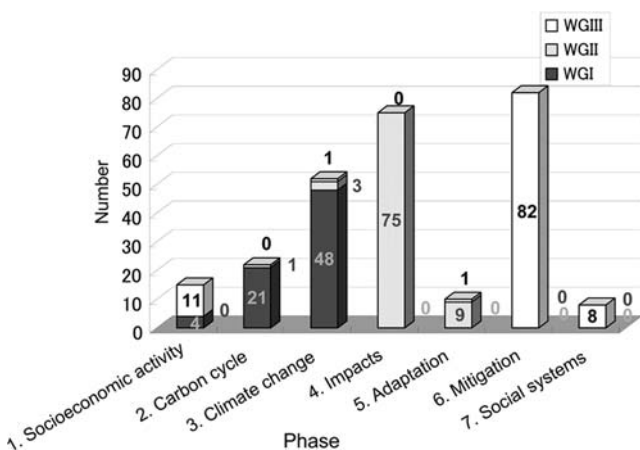


Fig. 4 Number of scientific results listed in IPCC AR4 for each phase

and a smaller number cover risk assessment. More of the results obtained in phase 6 deal with various short- and medium-term mitigating technologies, policies, measures, and methods and their economic costs, whereas fewer focus on long-term mitigation. In phase 3, there are 52 research results on observations of global and regional climate change in the atmosphere, ocean, and snow-covered areas, as well as future projections by climate models, primarily on the global level. The amount of scientific knowledge in these three phases is relatively large as compared with the other phases. In phase 2, 21 research results have been obtained. Most of these deal with radiative forcing of GHGs and aerosols and investigations of the causes of climate change, including mechanisms. In phase 1, there are 15 results dealing with emission sources and emission pathways for stabilization of GHG concentrations. Even fewer research results have been obtained in phases 5 and 7: 10 in adaptation (phase 5) and 8 in the

Table 2 Questions related to the major concerns of the Intergovernmental Panel on Climate Change (IPCC) working groups (WGs)**WGI**

Q1. Does the anthropogenic effect in the climate system cause global warming?

- (1) How do GHG emissions change?
- (2) In what way is radiative forcing due to anthropogenic effects?
- (3) Is climate change (global warming) observed?
- (4) How much is the mechanism of climate change understood?
- (5) Are there anthropogenic effects in the climate system?

Q2. What will the climate be like in the future? How reliable are the predictions of future climate?

- (1) Are the climate models validated? Are their results reliable?
- (2) How accurate are projections of future global and regional climate changes?

WGII

Q1. What are the observed impacts of climate change (global warming)?

- (1) What are the observed impacts in natural systems?
- (2) What is the observed influence on human systems?
- (3) How about the rate of appearance of impacts? (Has it accelerated?)
- (4) Where are the most seriously affected regions?
- (5) Are there multiple effects of climate change and other drivers?

Q2. What impacts will climate change have in the future?

- (1) What impacts will climate change have on sectors?
- (2) What impacts will climate change have on the regions and nations of the world?
- (3) What kind of sectors and what areas will suffer the most serious impacts?
- (4) When will impacts appear? How severe will they be? (Projection of the path of effect with time)

Q3. What is the dangerous level of the impacts of climate change and when will such impacts occur?

- (1) What is the level at which natural and biological systems will be irreparably affected?
- (2) What is the level at which food production will be irreparably affected?
- (3) What is the level at which the world economy will be irreparably damaged?
- (4) What is the level at which the irreparable influence will occur? (e.g., serious disasters)
- (5) What is the level at which long-term extreme events (e.g., melting of Greenland and West Antarctic ice sheets, shutdown of thermohaline circulation) will occur?

Q4. How effective are adaptations to climate change?

- (1) Have adaptations to climate change started?
- (2) To what extent can adaptations prevent adverse effects?
- (3) What kind of options are there for adaptation?
- (4) What are the elements that determine the effectiveness of adaptations?
- (5) How high are the costs of implementation compared with the costs of effects?

Q5. Which climate policies will contribute to sustainable development?

Table 2 continued

- (1) Will adaptation contribute to sustainable development?
- (2) What are the relationships between mitigation and adaptation? How can they be appropriately combined?

WGIII

Q1. How effective is mitigation in the short and medium term (until 2030)?

- (1) How great is the potential for GHG reduction?
- (2) How much is the reduction cost?
- (3) How is cost-effectiveness?
- (4) What are the global impacts of mitigation?
- (5) How much is reduction potential by sector?
- (6) How much is reduction potential by changing lifestyle and behavior?
- (7) How is carbon leakage?

Q2. What are the long-term mitigation options (after 2030)?

- (1) What are the emission pathways toward stabilization?
- (2) What are the stabilization scenarios?
- (3) How much is the cost of stabilization?
- (4) What decision-making for stabilization is required?

Q3. What kind of policies, measures, and instruments exist to mitigate climate change?

- (1) How is policy assessment?
- (2) How effective are mitigation policies?
- (3) How much is carbon price?
- (4) How effective is international cooperation?

Q4. Are there any gaps in knowledge among nations and societies?

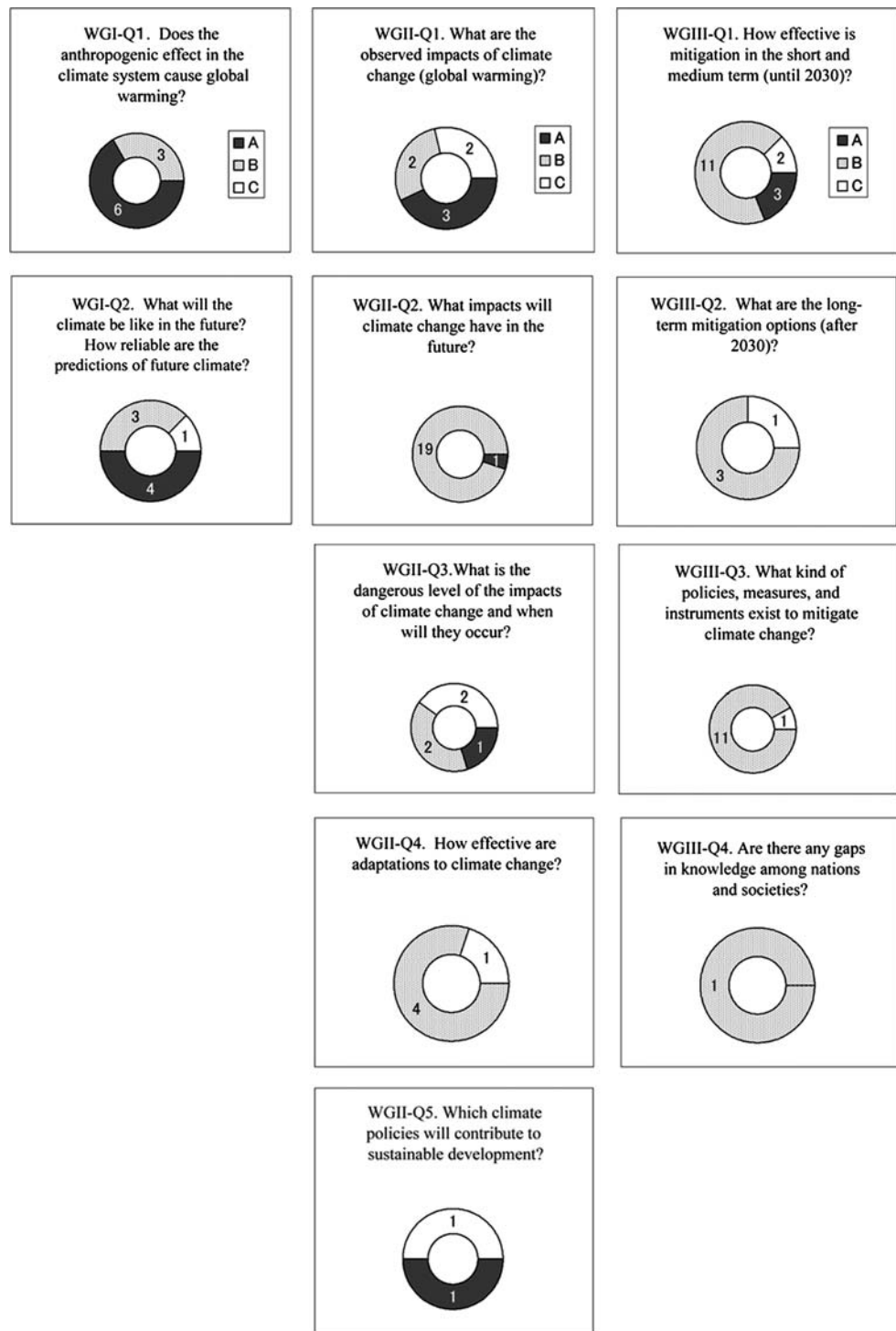
social system (phase 7). In phase 5, the necessity of adaptation has been recognized and practical uses of adaptation have been introduced, but there are almost no practical results on adaptation policy. In phase 7, research has focused on individual behavior, voluntary action, and industry management.

The content of IPCC reports was assumed to be policy relevant. The research results of SPMs were selected from the point of view of scientific and policy needs, and the difference in the numbers of results represents these characteristics. From the SPM analysis, it is found that a focus was placed on research such as acquiring scientific evidence of global warming and its causes, identifying the effects of climate change, and backing up mitigation options argued by various nations. Therefore, the numbers of scientific results for phases 2, 3, 4 and 6 are much higher than those of other phases.

Qualitative analysis: certainty of research results

In this section, we discuss the certainty of the scientific results. We defined the major concerns of the IPCC WGs and set the list of questions shown in Table 2. To examine the extent to which scientific knowledge has provided

Fig. 5 Certainty rankings for the scientific results generated by each WG. The number of IPCC AR4 results in each ranking category is shown for each question listed in Table 2



answers to the major concerns, and to clarify the level of certainty of those answers, we then reorganized the findings of IPCC AR4 in the form of answers to these questions. As well as considering the level of reliability placed by IPCC on the results, with the cooperation of two to three CLAs or LAs from each WG, we answered the questions and ranked the answers in terms of certainty on the basis of expert judgment as follows:

- A: Answered with high certainty.
- B: Partly answered (incomplete).
- C: No answer or still uncertain.

Results described as “virtually certain”, “very likely”, and “high confidence” in the SPMs were almost always ranked A. If there was difficulty in deciding between A/B and B/C or the judgment of CLAs or LAs was divided, we chose the lower rank. Figure 5 summarizes the certainties

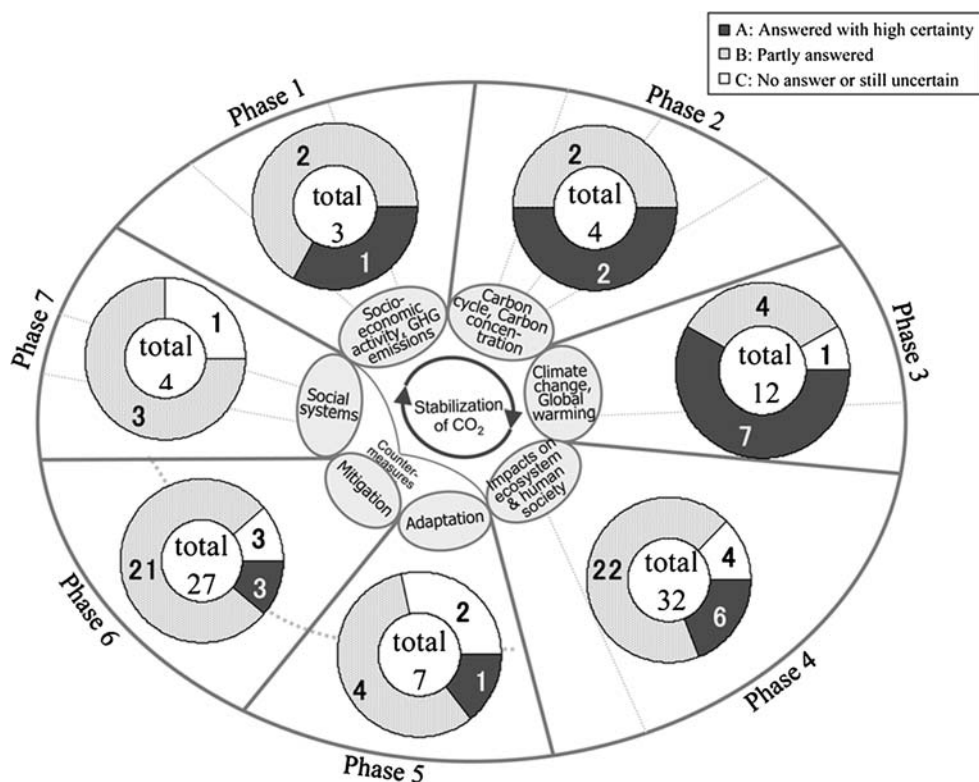
and uncertainties of the answers to the questions presented in Table 2. Detailed answers, with phase classifications and rankings, are given in the electronic supplementary material. When the certainty of answers is compared among the WGs, the proportions of answers ranked A–C is more meaningful than the actual number of questions ranked.

Two-thirds of answers were ranked A in WGI, which covers the anthropogenic effect on the climate system. Answers ranked A contain observations of increases in the average global air temperature (100-year linear trend of 0.74°C), average global temperature of the oceans, and average sea level (an average increase of 1.8 mm per year from 1961 to 2003), and a decrease in the amount of glaciers and snow cover in both hemispheres. Answers ranked A also contain new results of radiative forcing of GHGs. Climate models using both natural and anthropogenic forcings showed temperature change consistent with the observed temperature, whereas models using only natural forcings did not. From these results, it can be concluded that global warming exists, and that there is a high probability that global warming was derived from anthropogenic activity. On the other hand, answers on the effects of aerosols and the mechanisms of climate change remain uncertain. On the question of the future climate, half of the answers were ranked A. This is the result of the improvement in performance of climate models. There is almost no difference among scenarios in the predicted decadal

average warming by 2030. Climate models predict, with high levels of certainty, a warming of about 0.2°C per decade for the next two decades, an increase in the sea surface and ocean temperatures, a rise in global average sea level, a continued decline in continental glaciers and the amount of snow cover, and more frequent heat waves. However, projections of regional changes have higher levels of uncertainty. Climate–carbon cycle coupling is expected to add carbon dioxide to the atmosphere as the climate system warms, but the magnitude of this feedback is also uncertain. As a whole, the certainty of scientific answers of WGI is high as compared to those presented in the TAR.

Various impacts of climate change and global warming have been observed in some regions (WGII-Q1), and more than one-third of answers on observed impacts were ranked A. Specifically, significant changes in snow-covered areas, polar regions, and highlands, and a strong influence on terrestrial biological systems have been observed. However, as their lower rankings indicate, the effects on human systems are more difficult to discern, as are multiple effects. Only 1 answer out of 20 was ranked A for future impacts (WGII-Q2), and it identifies the regions that will suffer the most serious impacts. Almost all other answers were ranked B, primarily for predictions in sectors (water resources, ecosystems, food and forest products, coastal systems and low-lying areas, industry, settlement and

Fig. 6 Certainty rankings for answers to the key questions in each phase (Table 1). The number of IPCC AR4 results in each ranking category is shown for each phase



society, and health) and regions (Africa, Asia, Australia and New Zealand, Europe, Latin America, North America, polar regions, and small islands). There was one A-ranked answer to the third question, on the danger level of the impact. There is a high level of certainty for a decrease in cereal productivity at temperatures greater than 3°C above 1990 levels. However, the level at which an irreparable influence will occur is uncertain. Answers on adaptation (WGII-Q4) were almost all ranked B. Although the assessment of the effectiveness of adaptation is incomplete, the importance of adaptation has been recognized. There was one A-ranked answer to the question of whether adaptation will contribute to sustainable development (WGII-Q5), but methods of enhancing adaptation still need to be developed. A portfolio of adaptation and mitigation measures or sustainable development measures is recommended. As a whole, WGII has many partial answers. The certainty of answers to questions on regional and sectoral impacts needs to increase, and there is a need for more studies of adaptation policies.

For WGIII-Q1, concerning the effectiveness of short- and mid-term mitigation, 3 out of 16 answers were ranked A. These results indicate that there are co-benefits with health and energy security that will enhance cost savings, and that there is substantial potential for reduction of GHG emissions in the energy sector and through forest management. However, effectiveness varies by region and sector, and there are barriers to be overcome in many cases. For long-term mitigation (WGIII-Q2), there are only a few, somewhat uncertain results. There are several emission pathways, and decision-making about the appropriate level of global mitigation over time involves an iterative risk management process. Estimates of average cost for stabilization range from a 1% gain to a 5.5% decrease in global GDP in 2050, but costs for specific countries and sectors differ considerably from the global average. Almost all answers concerning mitigation policies and methods (WGIII-Q3) were ranked B. Research in this category includes studies on regulations and standards, taxes and charges, tradable permits, financial incentives, voluntary agreements, information instruments, research and development, governmental support for technology development and transfer, and CDM. There are uncertainties in carbon price, although it may create incentives for producers and consumers to significantly invest in low-GHG products, technologies, and processes. The effectiveness of international cooperation is also uncertain. There are gaps in knowledge among nations and societies (WGIII-Q4), but there was only one relatively uncertain result for this question. Throughout WGIII, many and varied mitigating options have been proposed, but there appears to be no single perfect solution. An optimum policy mix will be required to establish consensus and make those options effective.

Discussion: answers to key questions in the seven phases of mapping

We classified the answers from the previous section into our seven phases in the mapping and analyzed the certainty with which the scientific knowledge presented in IPCC AR4 answers the key questions of each phase (Table 1). The results of this analysis are presented in Fig. 6.

In response to the question posed in phase 1, it is clear that CO₂ emissions derived from fossil fuels have increased, from an average of 23.5 GtCO₂ per year in the 1990s to 26.4 GtCO₂ per year in 2000–2005. Although there are some uncertainties, it appears that a smaller proportion of CO₂ emissions is due to land use change, CH₄ emissions result predominantly from agriculture and fossil fuel use, and N₂O emissions are also from agriculture. CO₂ emission scenarios for six alternative categories of stabilization levels (from 445–490 to 855–1,130 ppm CO₂ eq.) have been proposed as future emission pathways, and results have indicated that the lower the stabilization level, the sooner this peak and decline would need to occur. However, it is still uncertain which pathway to take because outcomes depend on action taken by the world as a whole and by individual nations. The cost for each scenario is estimated as GDP share, but more accuracy is required for decision-making in regards to climate policy. There is a need for more concrete future scenarios for energy structure, industrial changes, and other emission sources.

In phases 2 and 3, the proportion of answers with a high degree of certainty is high (more than 50%). Answers to questions about the mechanism of climate change have become much clearer. New observational data, research on radiative forcing, and model calculations have clarified the view that recent global warming can be explained only by combining natural changes with the increase in anthropogenic GHGs, leading to the conclusion that recent human activities have caused global warming. Answers to questions concerning changes in thermohaline circulation, other drivers, and feedback systems have higher levels of uncertainty. In phase 3, the question about whether global warming has occurred has also been clearly answered. The climate has been getting warmer—the global average temperature has increased by 0.74°C in the past 100 years (1904–2005). Looking at the future climate, the estimated temperature increase ranges from 2.0 to 6.1°C, and an increased number of extreme events and other climatic change have also been predicted. Predictions provide clear answers for the near future climate, but predictions are less clear for the long-term future climate.

In phase 4, the impacts of climate change on ecosystems and human society have already become apparent, most

obviously changes in snow- and ice-covered areas and biological systems, as mentioned above. Polar regions, high latitude areas, and coastal areas have been identified as areas that will be vulnerable to climate change in the future, perhaps with severe impacts. Although the amount of research in this area has increased, impacts vary by sector and region, and there is still uncertainty in the answers. More studies for the detection of dangerous levels of impacts of climate change and of the multiple effects of other drivers are required. Risk management of global warming requires study, and adaptation will also be required. However, in phase 5, there are few research results and few certain answers. Adaptation has begun with existing technology, such as coastal revetment and agricultural adaptation. Options for adaptation are being studied, but the practical effectiveness and costs are not yet clear. Although there are needs for more integrated study of adaptation to address the unavoidable impacts resulting from warming due to past emissions, adaptation alone is not expected to handle all the projected effects of climate change. A portfolio of adaptation and mitigation measures is therefore required to diminish the risks associated with climate change. The design of such a portfolio remains as a future challenge.

Various studies, answers, and discussions have addressed, and continue to address, the mitigation questions posed in phase 6. There is a good deal of potential for a reduction in emissions in each sector through the use of available technologies for mitigation in the near future, especially in the energy infrastructure and forest management sectors with high reliability. Technology transfer is also effective. However, there is still a good deal of uncertainty about cost-effectiveness, carbon pricing, emissions reduction by sector, and policies for long-term mitigation. As a whole, in the absence of a clear global direction, the answers in this phase remain ambiguous despite the many suggestions. More cooperation and consensus building among nations are required to reach agreements, and appropriate measures are necessary to penetrate down to the local level to guarantee effective policy implementation. Moreover, to reduce GHG emissions drastically, a change in the structure of society itself is required, but the current answers on social systems (phase 7) provide few answers and low levels of certainty. Even though there is solid research potential and a demand for such research, results are quite limited in this phase. To date, research has been conducted on contributions from businesses (e.g., voluntary actions resulting from voluntary agreements) and behavioral change, but there have been no systematic studies and few certain scientific results in relation to the social system have been reported throughout the WGs.

The research results presented in IPCC AR4 represent a marked improvement over those presented in TAR, especially the physical research on climate change. There remains, however, a need to improve the more practical studies and social science research if successful action is to be taken to address global warming. Examples include the appropriate implementation of a portfolio of adaptation and mitigation strategies, and more concrete societal assumptions for stabilization. It is important to fill in gaps in knowledge through education and capacity building. Studies on improving the participatory process of citizens; the effects of culture, ethics, and religion; and the cooperation of various actors are also required. Research in the field of social systems has been weak. The IPCC (1995) report on the economic and social dimensions of climate change focuses primarily on economic aspects and equity considerations between developing and developed countries. Of the global warming research programs, the Japanese government budgeted the least amount for social systems (TIGS 2008). Most of the United States government's global-change budget has focused on upstream uncertainties in the natural sciences, and little has been budgeted for social and behavioral sciences (Pielke 1995; Nordhaus and Popp 1997). The supply of and demand for science in decision-making has not been in alignment (Sarewitz and Pielke 2007). It is important that scientific knowledge is communicated effectively within society, so that science can be utilized effectively and new technologies and policies that address climate change are accepted. Moreover, as well as taking effective measures against global warming, it is important to assess whether these measures are compatible with other problems and contribute to the larger goal of achieving a sustainable society.

Summary and conclusions

To get a complete picture of the current state of scientific knowledge regarding global warming, we developed a mapping framework for global warming issues. The framework consists of seven phases based on the interaction of nature and human society. We then applied the research results presented in the SPMs of IPCC AR4 to the mapping and analyzed the results in each phase quantitatively and qualitatively. Our conclusions can be summarized as follows.

- The results presented in IPCC AR4 have a high proportion of high certainty answers to questions on the carbon cycle and carbon concentration (phase 2), and climate change and global warming (phase 3). These answers identify the cause of recent global warming and predict future climate change.

- There is a large amount of information on impacts on the ecosystem and human society (phase 4) and mitigation (phase 6), although the results presented do not always have a high level of certainty. The impacts and effective mitigation options will vary by regions and sectors.
- While there are only a few answers to the questions posed regarding adaptation (phase 5), practical applications have begun to be implemented. More options are required.
- Throughout all the WGs, there are still only limited answers to the key questions about a low carbon society posed in the phases on socioeconomic activity and GHG emissions (phase 1) and social systems (phase 7).

Mapping global warming research results in such a way has made it possible for us to better understand the overall state of current scientific knowledge regarding global warming. With the application of this type of mapping framework, we were able to identify which areas of research have progressed and which are lagging behind with regard to global warming. This is important when society decides future directions of research. On the other hand, this paper did not validate sufficiently to what extent the answers from science match the needs of society. How science should answer the needs of society, which change widely and often include individual values or political will, is a future challenge to be discussed in the study of sustainability science. Nevertheless, this mapping approach provides a framework that will also be useful in organizing the various needs of society.

Since the publication of IPCC AR4, there have been discussions about the next IPCC report (AR5). Some scientists have argued that the *Special Report on Emissions Scenarios* (SRES) (IPCC 2000) is outdated and have demanded more realistic assumptions for emissions pathways (Pielke et al. 2008; Schiermeier 2008). Other scientists have discussed seeking a new IPCC step, one that puts more focus on solutions (Raes and Swart 2007; Tollefson 2007). We hope the findings of the present study will support setting the future directions of research and of the IPCC framework toward establishing a low-carbon and sustainable society.

Acknowledgments This study was supported by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) through the Special Coordination Funds for Promoting Science and Technology. We sincerely appreciate the kind cooperation of the CLAs and LAs (Dr. Akira Noda at Meteorological Research Institute for WGI, Dr. Hideo Harasawa at National Institute for Environmental Studies for WGII, and Dr. Mikiko Kainuma at National Institute for Environmental Studies and Prof. Ryuji Matsuhashi at the University of Tokyo for WGIII). We also appreciate the continuous support of Dr. Makoto Tamura at Ibaraki University and Dr. Masahiro Sugiyama at the University of Tokyo, and the kind cooperation of other FP-GW members.

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